Towards the application of MNG-loaded slow wave structures in spatial harmonic magnetrons

Nasrin Nasr Esfahani, Klaus Schünemann

Institut für Hochfrequenztechnik
Technische Universität Hamburg-Harburg
21071, Hamburg, Germany
e-mail: nna@tf.uni-kiel.de

Abstract

In this paper, it is shown that MNG (negative permeability) loaded slow wave structures (anode blocks) can considerably improve the important characteristics of spatial harmonic magnetrons (SHMs) such as output power and efficiency. First, theoretical limitations of conventional anode blocks are demonstrated. Then, the results of rigorous analysis of MNG-loaded slow wave structures which show their potential in resolving limitations of conventional anode blocks are briefly presented. Finally, warm cathode operation of an MNG-loaded SHM and a conventional SHM are simulated and compared.

1. Introduction

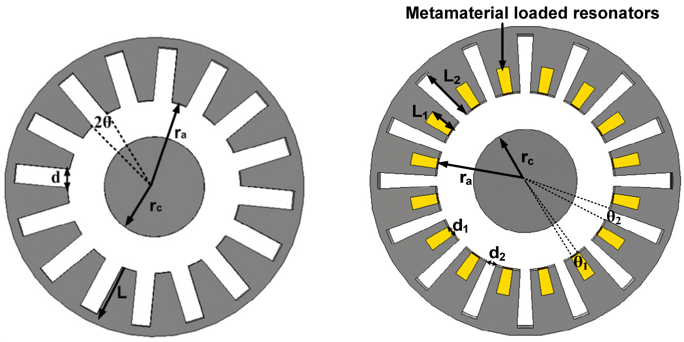
Although SHMs resolve the fundamental limitations of classical magnetrons in millimeter wave and sub-millimeter wave frequencies [1], [2] i.e., considerable decrement of cavity dimension and impractical increment of the required magnetic field, they suffer from a fundamental drawback which is the low amount of efficiency and output power in comparison with the classical π-mode counterparts [1], [2] . In the next sections, the bases of such a fundamental drawback are revealed and the improvement provided by the use of MNG-loaded slow wave structures are presented.

2. Theory of conventional anode blocks

Considering the peculiar conditions governing the SHMs and simplifying the equations related to motion of electrons, we have developed a simplified theory which reveals that in a SHM the only component of the RF-field which mainly affects electron trajectories and power generation is the φ directed electric field (E_φ) in the areas close to the anode structure. Considering conventional anode structures (Fig.1(a)), E_φ close to the anode may be written as:

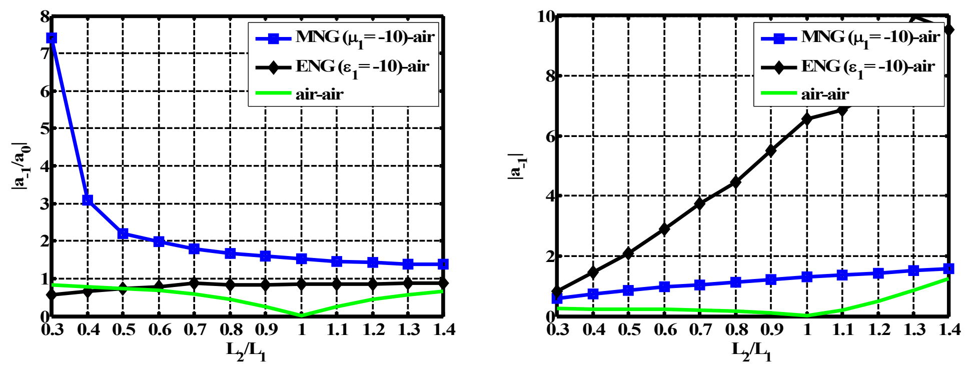
$$E_\varphi(\varphi) = \sum_{m=-\infty}^{\infty} a_m e^{j\gamma_m \varphi}; a_m = \frac{N}{\pi}\left(\frac{\sin\gamma_m\theta}{\gamma_m}\right); \gamma_m = mN + n,\ \ m = ..., -1, 0, 1, ...; n = 1, 2, ..., \frac{N}{2} \tag{1}$$

where N and 2θ are the number of side resonators and resonators opening, respectively, m designates the order of spatial harmonic and n is called the mode number. In this nomenclature the phase difference between the adjacent resonators is 2πn/N, therefore n=N/2 mode refers to π-mode and n=N/4 mode refers to π/2-mode. a_0 and a_{-1} are usually referred to as amplitude of the fundamental spatial harmonic and the amplitude of the first backward one, respectively. Despite the classical π-mode magnetrons which utilize the interaction of the fundamental harmonic of the π-mode with electrons, SHMs utilize the interaction of the first backward harmonic of the π/2 or neighboring mode. As can be easily deduced from Eq.(1), the amplitude of this harmonic in conventional anode structures is always weaker than the amplitude of the fundamental one. This causes an inefficient interaction of electrons with the synchronous harmonic and results in poor efficiency. The absolute values of a_{-1} are also limited to small values (for $\pi/2$-mode, $|a_{-1}|<0.42$). This can also be another reason for poor efficiencies. Finally, it can be deduced that conventional anode structures impose two fundamental limitations, i.e., $|a_{-1}/a_0|<1$ and $|a_{-1}|<0.42$ on the spatial harmonic operation mode. In the next section, it will be shown that using an MNG-loaded anode block these limitations can be resolved.



(a) (b)

Fig. 1: (a) Conventional anode structure, (b) metamaterial loaded anode structure



(a) (b)

Fig. 2: (a) $|a_{-1}/a_0|$ and (b) $|a_{-1}|$ for different types of anode blocks considering the special case in which: r_a=2.25mm, r_c=1.3mm, d_1= d_2=0.25mm and L_1=2mm

3. Theory of MNG-loaded anode blocks

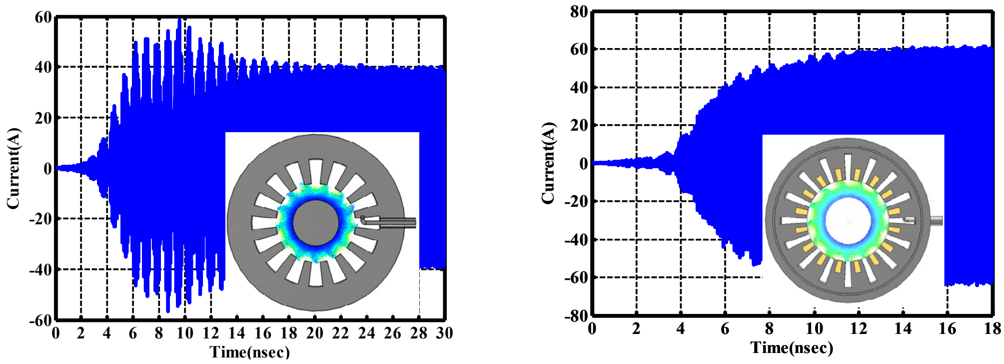
Fig.1(b) depicts the geometry under consideration. It consists of two different resonators per period of lengths L_1 and L_2, and openings θ_1 and θ_2. One category of these resonators is filled with air while the other category (shown in yellow in Fig.1(b)) can be filled with an MNG medium, ENG medium or air. We call these different types of anode blocks MNG-air, ENG-air and air-air type. Considering these anode types, the amplitude of different harmonics of E_φ can be determined using rigorous electromagnetic analysis. The results of this analysis can be summarized in the following equation

$$a_m = \frac{N}{2\pi}\left(\frac{\sin\gamma_m\theta_1}{\gamma_m}\right).(1+\frac{(-1)^m E_2}{E_1}\frac{\sin\gamma_m\theta_2}{\sin\gamma_m\theta_1}) \quad \gamma_m = m\frac{N}{2}+n;\; m=\ldots,-1,0,1,\ldots;n=1,2,\ldots,\frac{N}{4} \tag{2}$$

where E_2/E_1 shows the ratio of the electric field amplitudes at the apertures of the two different resonators. This ratio which is a complicated function of resonator and interaction space characteristics can be determined considering boundary conditions. Eq.2 shows the fact that through the adjustment of E_2/E_1, the fundamental harmonic can be diminished or even suppressed. E_2/E_1, $|a_{-1}/a_0|$ and a_{-1} have been calculated considering MNG-air, ENG-air and air-air type anode blocks. The results, which some examples of them are shown in Figs. 2(a) and (b) reveal that only MNG-air type anode block can increase the $|a_{-1}/a_0|$ to values greater than one. This type of anode can also increase the absolute values of $|a_{-1}|$. In the next section, warm cathode analysis of an MNG-air type anode structure will be presented.

3. Warm cathode simulation results

Dimensions of the MNG-loaded anode and the conventional one together with the values of $|a_{-1}/a_0|$ and $|a_{-1}|$ are summarized in table 1. As can be deduced from this table, $|a_{-1}/a_0|$ and $|a_{-1}|$ for the MNG-loaded anode have been increased by approximately 3.1 and 2.6 times, respectively. Warm cathode operation of the above mentioned SHMs has been simulated using CST –Particle Studio [3] under the same conditions[1]. The simulation model of the magnetron together with distribution of electrons has been shown in the insets of Figs. 2(a) and (b). The presence of 13 electron bunches (γ_{-1}=13) confirms the excitation of n=3 (π/2-1) mode. The output currents corresponding to the two designs, measured at the coaxial outputs, are shown in Figs. 3(a) and (b), respectively. Considering these figures and table 2 which summarizes the important warm cathode characteristics of the two designs, it can be deduced that, the efficiency and output power of the MNG-loaded SHM are increased by more than about two times the efficiency and output power of the conventional SHM.



(a) (b)

Fig. 3: Output current and space charge distribution of; (a) Conventional SHM, (b) MNG-loaded SHM.

Table1: Geometrical characteristics of the two SHMs.

	r_a(mm)	r_c(mm)	L_1(mm)	L_2(mm)	d_1(mm)	d_2(mm)	N	n	$\|a_{-1}/a_0\|$	$\|a_{-1}\|$
MNG(μ_1=-10)-loaded	2.25	1.3	0.65	1.44	0.25	0.25	32	3	1.71	1.11
Conventional	2.25	1.3	1.26	-	0.44	-	16	3	0.55	0.42

Table 2: Output characteristics and DC operating point of the two SHMs.

	Output power	Anode current	efficiency	Frequency
MNG(μ_1=-10)-loaded	90kW	27	26%	38.5GHz
Conventional	40kW	25	12.6%	38.5GHz

4. Conclusions

It has been shown that conventional anode structures impose fundamental limitations on the spatial harmonic operation mode which results in inefficient, Low output power SHMs. The ability of novel MNG-loaded anode blocks in resolving these limitations and increasing output power and efficiency has been demonstrated and validated through the use of warm cathode simulations.

References

[1] V. Naumenko, A. Suvorov, and A. Sirov, Spatial-harmonic magnetrons-THz electromagnetic radiation sources., Proceedings of *International conference on microwave and milllimeter wave technology*, pp. 1199-1201, Nanjing, China, 21-24 April 2008.

[2] K. Schünemann , S. V. Sosnytskiy, and D. M. Vavriv, Self-consistent simulation of the spatial-harmonic magnetron with cold secondary-emission cathode" IEEE transaction on electron device, vol. 48, no. 5, pp. 993-998, 2001.

[3] CST –Particle Studio (2012). [online] Available:http://www.cst.com.

[1] In warm cathode simulations an appropriate lossy Drude model has been considered for the MNG medium.

ISBN 978-952-67611-2-1